Beamline 12.0.1

EUV Optics Testing and Interferometry, Angle- and Spin-Resolved Photoemission

Controlling contamination in Mo/Si multilayer mirrors by Si surface-capping modifications

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Controlling Contamination in Mo/Si Multilayer Mirrors by Si Surface-capping Modifications

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INTRODUCTION

The present experiments helped determine the influence of the Si capping layer thickness in Mo/Si multilayer mirrors (MLMs) on the initial carbon (C) buildup on the mirrors when used in an extreme ultraviolet (EUV) + low pressure hydrocarbon (HC) vapor environment. The intent of this work was to broaden the approach taken to fabricate multilayer mirrors, by proposing that MLMs be made so that they have not only high initial reflectances but also low C buildup when used in EUV + HC environments. Carbon buildup is undesirable since it absorbs EUV radiation and reduces MLM reflectivity.

Previous work [1-4] on non-multilayer optical elements in synchrotron beamlines has shown that the "cracking" of hydrocarbons adsorbed on the optical surfaces leads to deposition of carbon onto these surfaces. "Cracking" is the name given to the process in which adsorbed, potentially volatile hydrocarbons are transformed into stable carbonaceous species on a surface. In these previous studies [2-4], it was determined that this cracking was caused by photoelectrons emitted from the metallic optical surfaces.

When EUV radiation is incident onto a MLM there is a sinusoidally varying, standing wave electric field both inside and outside the MLM structure. This incident photon radiation creates a standing wave, electric field intensity (and similarly modulated photoemission) with a period of half the wavelength of the incident EUV light. Since the cracking of adsorbed hydrocarbons is likely caused by photoelectrons [2-4], in principle the initial carbon contamination on MLM surfaces could be reduced by appropriately adjusting the electric field intensity at the uncontaminated MLM/vacuum interface so the field intensity is near a minimum.

One way to vary this intensity at the MLM/vacuum interface is through intentional changes in the thickness of the MLM Si capping layer. A set of Mo/Si MLMs deposited on Si wafers was fabricated such that each MLM had a different Si capping layer thickness ranging from 2 nm to 7 nm. Each was deposited such that maximum reflectance occurred at normal incidence for photons of 13.4 nm wavelength and had Mo/Si bilayer pairs about 6.9 nm thick, with Mo/(Mo+Si) thickness ratios of 0.4. These samples were used in subsequent EUV+HC tests.

RESULTS

It was found that the capping layer thickness affected both the initial MLM reflectivity and the "carbonizing" tendency on the MLM when exposed to EUV(13.4 nm, ~ 0.5 mW/mm^2) + HC vapors (pressures estimated to be $< 10^{-8}$ Torr). Measurements of the uncontaminated, absolute reflectivities were performed on the Calibration and Standards beamline at the ALS and are given in Figure 1 below. Figure 2 below shows the relative reflectivities (reflectivity/original reflectivity) for all samples which were subsequently exposed to EUV + HC vapors.

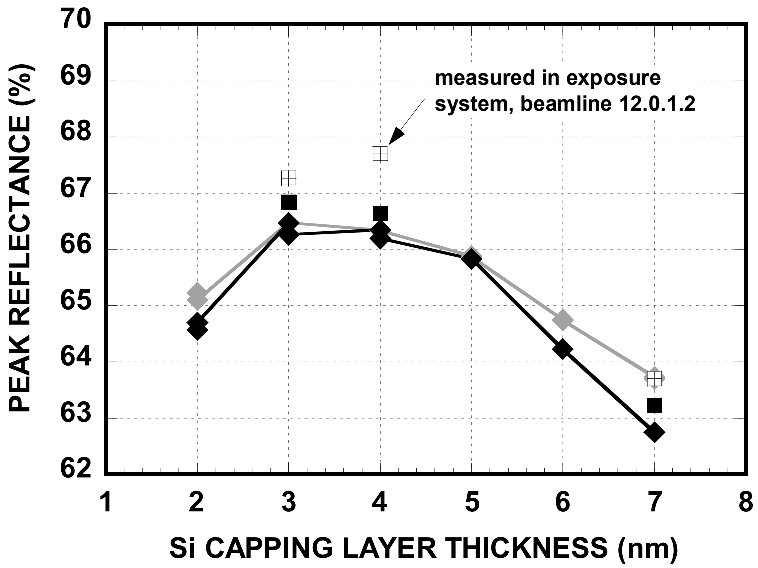

Figure 1. Absolute reflectances of all samples in used in this study. Reflectances were measured in regions not exposed to EUV+HC vapors. Values measured on beamline 12.0.1.2 are shown as squares with inset crosses. All other values were measured on beamline 6.3.2 before the experimental runs (gray points) and after experimental runs (black points).

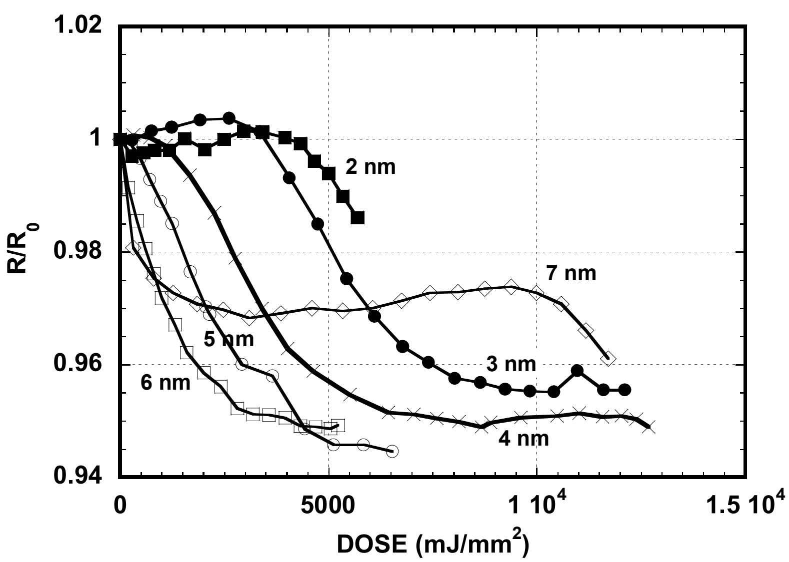

Figure 2. Relative reflectances) of samples with different capping layers exposed to EUV+HC as a function of photon dose.

In these samples, the doses where the relative reflectivities decreased most rapidly (e.g., at ~ 5000 mJ/mm^2 for the 3 nm capped sample) were also the doses where peaks in photocurrent emission occurred. These observations were consistent with the proposed correlation between photoemission (or near-surface electric field intensity) and carbon buildup. The results in both these figures also show that the use of a 3 nm capping layer on a Mo/Si MLM represents an improvement over the 4 nm layer since the 3 nm sample has both a higher absolute reflectivity and better initial resistance to carbon buildup. A typical Mo/Si MLM has a ~ 4.3 nm Si cap.

SUMMARY

The results of this work have shown that varying the silicon capping layer can change the characteristics of carbon buildup on a Mo/Si MLM optic. The data obtained indicated that a ~3 nm Si- capped Mo/Si MLM was the MLM which not only had the highest as-received reflectivity but also maintained that reflectivity the longest under EUV+HC vapor pressure exposure of the samples studied – those with Si capping layers from 2 nm to 7 nm. Using a 3 nm instead of 4 nm thick Si capping layer on Mo/Si MLMs should produce improved optic lifetimes and should likewise help reduce downtimes in EUVL tools using such optics. This work also showed that there is a strong correlation between the EUV-induced photocurrent from a MLM and its reflectivity, with maxima in the photocurrents occurring when relative reflectivity loss rates were the highest. This observation suggested that the carbon buildup was also correlated with photoemission, with higher carbon growth rates coincident with higher MLM photoemission. However, since the maxima in surface electric fields at the MLM are correlated with photoemission maxima, the current data did not allow a differentiation between the mechanisms of direct photon vs. photoelectron-caused hydrocarbon cracking. The current data were consistent with the existence of a standing wave electric field near the MLM surface and suggest that its form profoundly affected carbon contamination of MLMs. The results further suggested that the strategy of minimizing the near- surface electric field at the MLM/vacuum to reduce carbon buildup should be applicable to MLM systems other than conventional Mo/Si, including Mo/Si with other capping layers and MLMs using other material combinations

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Extreme ultraviolet interferometry: measuring EUV optical systems with sub-Å accuracy

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INTRODUCTION

The semiconductor manufacturing industry has selected extreme ultraviolet (EUV) lithography as the leading candidate for circuit fabrication with critical dimensions below 70 nm, beginning approximately in the year 2007. Current photo-lithography technologies use much longer ultraviolet light wavelengths and achieve critical dimensions as small as 130-nm. Research conducted during the past decade has demonstrated the feasibility of every aspect of EUV lithography, but some major challenges for its implementation still remain. Using such a short wavelength of light, dramatically reduces the error budget for the fabrication and assembly of projection lenses that focus and demagnify EUV images. The suggested RMS wavefront-error tolerances for EUV optical systems are in the $\lambda_{EUV}/50$ range (0.25 nm). The error tolerances on the individual mirrors that make-up such lenses are even tighter. Building optics of this unprecedented high quality is only possible if accurate measurement tools are available.

The EUV interferometers operating on ALS beamlines 12.0.1.2[1,2] and 12.0.1.3[3] have been designed to measure sub-angstrom-sized aberrations in EUV optical systems. In 2002, scientists from LBNL's Center for X-Ray Optics (CXRO) measured the second of two lithographic quality large-field EUV projection lenses.[4,5] These optics were designed an produced by a collaboration of Lawrence Berkeley, Lawrence Livermore (LLNL), and Sandia National Laboratories (SNL), funded by an industry consortium called the EUV LLC, which is comprised of Intel, AMD, Micron Technology, Motorola, IBM, and Infineon.

The optics are assembled and aligned using a state-of-the-art visible-light interferometer at LLNL,[6] and are then transported to the Advanced Light Source for measurement at EUV wavelengths. Because the EUV mirror coatings are specifically designed for high reflectivity in a narrow EUV wavelength range, measurements performed "at-wavelength" give essential feedback about the performance of the optic. EUV testing also provides an opportunity to validate the measurements made with visible-light interferometry. Through a careful comparison of the EUV and visible-light measurements, systematic measurement differences can be identified and resolved, and the accuracy of both systems can be improved.

A NOVEL EUV INTERFEROMETER DEVELOPED FOR ULTRA-HIGH-ACCURACY

Designed for exceptionally high-accuracy, the interferometers operating at Beamline 12.0 use the high brightness and coherence properties uniquely available at an ALS undulator beamline. Diffraction from tiny "pinhole" apertures placed at the foci of EUV beams, produces nearly perfect spherical waves that serve as reference waves in the interferometer. The interferometer compares these spherical reference waves to the aberrated waves produced by the optical system under test. Differences smaller than a tenth of an angstrom can be observed; the interferometer's reference-wave accuracy has been measured to be in the half-angstrom range.

Where high-brightness EUV light is available, the phase-shifting point-diffraction interferometer (PS/PDI)[7,8,9] has emerged as the high-accuracy system measurement tool of choice. A schematic of the optical design of the PS/PDI is shown in Fig. 1. Open-stencil pinholes smaller than 100-nm diameter are used to test the latest high-quality EUV optics. A coarse grating beam splitter placed before the test optic divides the beam into multiple diffractive orders that are brought to spatially separated foci in the image-plane. One beam, the *test* beam, containing the aberrations of the test optical system, is allowed to pass through a large window in an opaque mask placed in the image-plane. A second beam, the *reference* beam, is spatially filtered by a pinhole smaller than the diffraction-limited resolution of the test optic, and becomes the spherical reference wave. These two beams overlap to produce an interference fringe pattern that is detected by an EUV CCD detector. The interference pattern may be interpreted as a coherent comparison of the aberrated test beam with the nearly-perfect spherical reference beam; the fringe pattern thus reveals the aberrations in the test optic. Translation of the grating beam splitter is used to introduce a controlled relative phase-shift between the test and reference beams, allowing phase-shifting interferometry techniques to be employed.

The PS/PDI now serves as the accuracy standard for other EUV system metrologies, including visible-light interferometry and alternate EUV interferometry methods being pursued by the CXRO and others.

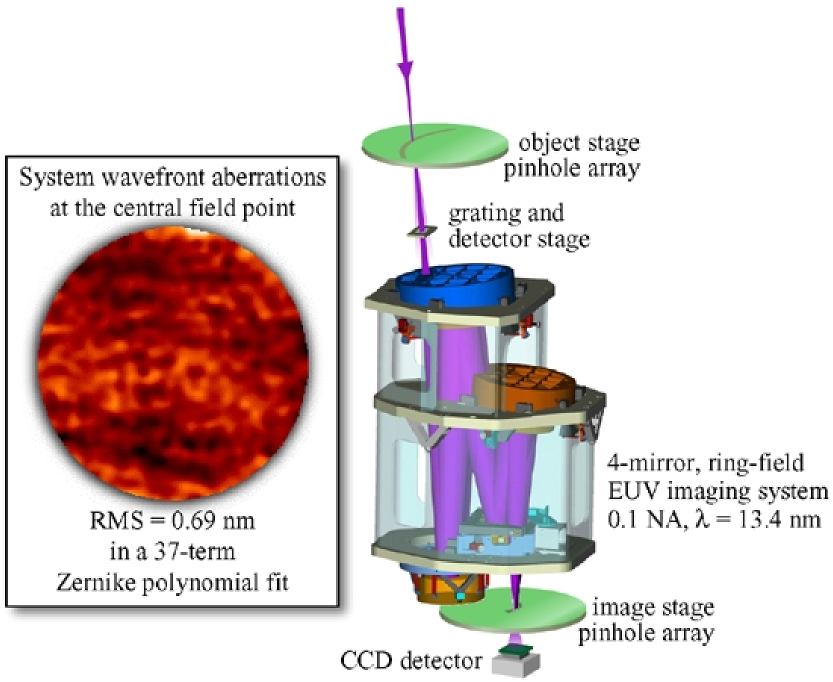

Figure 1. The extreme ultraviolet phase-shifting point diffraction interferometer (EUV PS/PDI) constructed at Beamline 12.0.1.3 for the measurement of lithographic quality projection optics for EUV lithography. The interferometer spatially filters coherent EUV light from ALS to produce reference wavefronts of exceptionally high spherical accuracy. System wavefront quality measurements are made across the large field of view. The aberration data is used to align the four-mirror system, and to predict imaging performance.

AN ACCURACY STANDARD FOR EUV OPTICS TESTING

In the future, as the quality and resolution of EUV optical systems improves, the demands on accurate wavefront metrology become ever higher. The high accuracy afforded by the EUV interferometry performed at ALS Beamline 12.0 can serve a major role in the development of alternate measurement techniques, both visible-light and non-synchrotron-based EUV methods. Since the ultimate proof of the accuracy of lithographic optical system testing comes from printing-based tests, the beamline's illumination system has been modified to accommodate printing experiments as well. These experiments are the subject of a separate abstract in this compendium.

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Static Microfield Printing at BL12 with Advanced EUV Lithographic Optics

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1. INTRODUCTION

Extreme ultraviolet (EUV) projection lithography is now the leading contender for *next-generation lithography* beyond the limits imposed by currently used refractive optical systems. Because EUV systems utilize resonant reflective coatings,[1] at-wavelength characterization,[2] including system wavefront metrology, has played an essential role in the development of EUV lithographic optics.

To meet the at-wavelength wavefront metrology challenge, an EUV-compatible diffraction-class interferometer, the phase-shifting point diffraction interferometer (PS/PDI), has been developed and implemented at Lawrence Berkeley National Laboratory.[3] As described in a separate abstract in this compendium, the PS/PDI has been demonstrated to have a wavefront measurement accuracy of better than $\lambda_{EUV}/200$ (0.67 Å) within a numerical aperture (NA) of 0.1.[4]

While PS/PDI wavefront interferometry[5-7] is now routinely used for the characterization and alignment of EUV lithographic optics,[8,9] the ultimate performance metric for lithographic systems is printing in photoresist. Direct comparison of imaging and wavefront performance is also useful for verifying and improving the predictive power of wavefront metrology under actual printing conditions. To address these issues in the most flexible and time-efficient manner, static, microfield printing capabilities have been added to the EUV PS/PDI. In printing configuration, the test station is referred to as the Static Exposure Station (SES). This at-wavelength test station has been designed to test the 4×-reduction projection optics boxes[9] developed for implementation in the EUV Engineering Test Stand (ETS)[10] now operational at the Virtual National Laboratory (the VNL is a partnership between Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories).

Two EUV 4×-reduction optic systems have been developed as part of the EUV LLC's EUV lithography program with the first developmental set of optics (the Set-1 optic) currently operating in the ETS.[11] The second much higher quality optic[4,12] (the Set-2 optic) is currently undergoing microfield static printing characterization in the SES. Although this optic is destined for integration into the ETS for full-field scanned imaging, valuable early learning has been obtained by the new microfield static printing capabilities of the SES.

A static imaging system, the SES has a microfield size of approximately 100 μm at the wafer. However, the full 1-inch arc field can be covered one microfield at a time by moving the entire system relative to the stationary illumination beam. The SES works with the same reflection masks used in the ETS. In addition, the SES supports variable partial coherence (σ) ranging from approximately 0 to 1 as well as enabling a programmable pupil fill.

The biggest challenge for the implementation of printing capabilities at the EUV interferometry beamline was modifying the illumination coherence. Relevant printing studies with lithographic optics require illumination partial coherence (σ) of approximately 0.7. This σ value is very different from the coherent illumination requirements of the EUV PS/PDI and the coherence properties naturally provided by synchrotron undulator beamline illumination (<0.05).[13,14] Adding printing capabilities to the PS/PDI experimental system has thus necessitated the development of a novel illumination system capable of quantitatively reducing the inherent coherence of the beamline.

1. ADDING PRINTING CAPABILITIES TO THE PS/PDI

Although the illumination issue is the most fundamental of the changes required to implement printing in the EUV interferometry tool, several other modifications were necessary to enable printing in a system originally designed for interferometry.

In contrast to the transmission configuration of the PS/PDI,[3] relevant printing studies require a reflection mask (reticle) to be used and, therefore, the illumination must come from below the object plane. This is achieved by providing clearance for the beam to pass downward through the object plane before it is redirected upward to illuminate the reflection reticle (Fig. 1). The final illuminator optic used to redirect the beam upward is positioned at the location normally occupied by the PS/PDI grating.

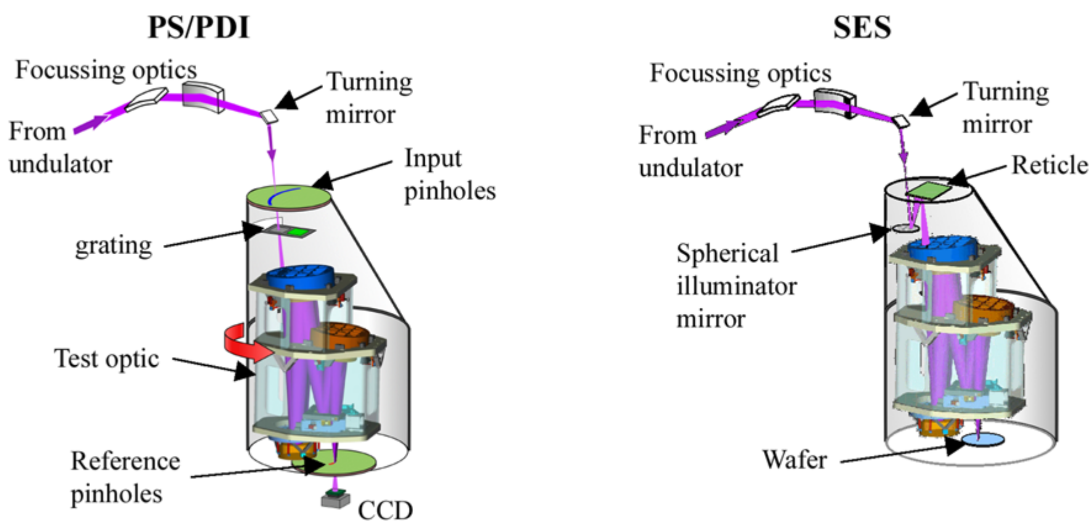

Fig. 1. Schematic of at-wavelength system characterization test stand in both PS/PDI and SES modes. PS/PDI endstation in interferometry mode. In SES mode, the beamline illumination passes through the object plane and is redirected upward using a spherical mirror that replaces grating used in interferometry mode.

Another important issue for the SES was image-plane-stage speed. The original flexural, picomotor-driven stage design was optimized for extremely high resolution (better than 10 nm) at the expense of speed (the original stage speed was approximately 1 μm/s). In imaging mode with no overlay capabilities, however, stage resolution is not important; yet having improved stage speed enables the acquisition of focus-exposure matrices (FEM) in a reasonable amount of time. To address the lateral-scanning speed issue a nested-stage solution has been implemented providing a 20× increase in stage speed while maintaining accuracy when required. This new stage design enables the acquisition of large FEMs (13×13) in approximately 1 hour.

Also newly implemented for printing operation were an electrostatic chuck for the wafer and a vacuum load-lock wafer-transfer system.

1. PRINTING CHARACTERIZATION

The ETS Set-2 optic[9] is a 0.1 numerical aperture (NA) optic designed for 100-nm critical dimensions (CD). At the central field point, where all subsequent printing results are presented, the Set-2 optic has a wavefront quality of 0.69 nm or 52 mwaves. A detailed description of the interferometric characterization of the Set-2 optic can be found in Refs. 4 and 12.

Although designed for 100-nm CD, the Set-2 optic is capable of higher-resolution performance. Figure 2 shows a series of equal line-space images ranging from 90-nm CD down to 60-nm CD. All images were recorded with conventional disk illumination and a partial coherence of 0.8. In Fig. 3 equal line-space printing down to 50-nm is demonstrated. This was achieved using resolution-enhancing dipole illumination, created by the novel coherence-controlling illuminator. This illumination improves the resolution in the vertical direction at the expense of other orientations.

In addition to using resolution-enhancing illuminations, it is also possible to decrease printed-line size for loose-pitch features through dose control. Figure 4 shows 39-nm 3:1 pitch elbows printed by overdosing features coded as 80-nm 1:1 on the reticle. These results were obtained using conventional disk illumination with a partial coherence of 0.7.

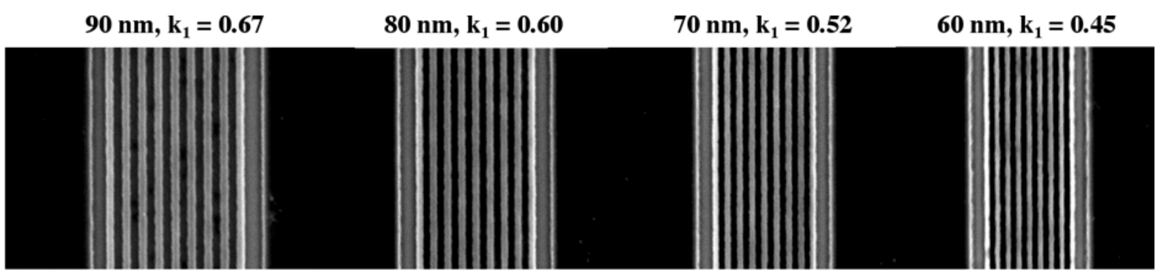

Fig. 2. Series of dense-line images ranging from 90-nm CD down to 60-nm CD. All images were recorded with conventional disk illumination and a partial coherence of 0.8.

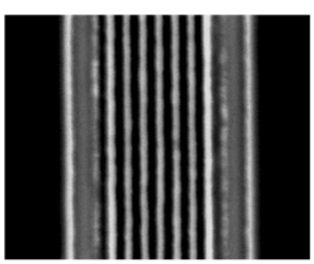

Fig. 3. 50-nm dense line printing ($k_1 = 0.37$) achieved with dipole illumination.

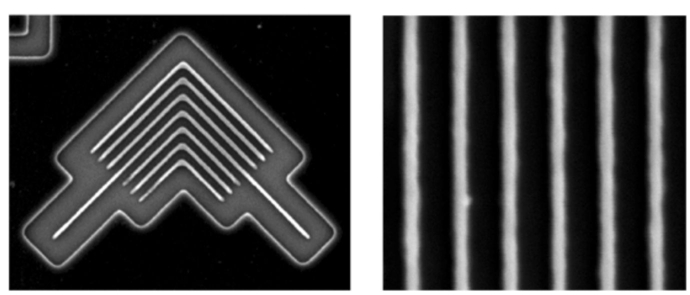

Fig. 4. 39-nm 3:1 pitch elbows and lines printed by overdosing features coded as 80-nm 1:1 on the reticle. Conventional disk illumination with a σ of 0.7 was used.

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